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ORIGINAL PAPER

A process model for simulating net primary productivity (NPP) based on the interaction of water-heat process and nitrogen: a case study in Lantsang valley

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Abstract: Terrestrial carbon cycle and the global atmospheric CO_2 budget are important foci in global climate change research. Simulating net primary productivity (NPP) of terrestrial ecosystems is important for carbon cycle research. In this study, a plant-atmosphere-soil continuum nitrogen (N) cycling model was developed and incorporated into the Boreal Ecosystem Productivity Simulator (BEPS) model. With the established database (leaf area index, land cover, daily meteorology data, vegetation and soil) at a 1 km resolution, daily maps of NPP for Lantsang valley in 2007 were produced, and the spatial-temporal patterns of NPP and mechanisms of its responses to soil N level were further explored. The total NPP and mean NPP of Lantsang valley in 2007 were 66.5 Tg C and 416 $g{\cdot}m^{-2}{\cdot}a^{-1}$ C, respectively. In addition, statistical analysis of NPP of different land cover types was conducted and investigated. Compared with BEPS model (without considering nitrogen effect), it was inferred that the plant carbon fixing for the upstream of Lantsang valley was also limited by soil available nitrogen besides temperature and precipitation. However, nitrogen has no evident limitation to NPP accumulation of broadleaf forest, which mainly distributed in the downstream of Lantsang valley.

Keywords: net primary productivity; nitrogen cycle; Lantsang valley; boreal ecosystem productivity simulator

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Introduction

Studies on the terrestrial carbon cycle and the global atmospheric CO_2 budget are paid most attentions in global climate change research. A key component of the terrestrial carbon cycle is net primary productivity (NPP), which is defined as the difference between accumulative photosynthesis and accumulative autotrophic respiration by green plants per unit time and space (Matsushita et al. 2004). Accurate estimate of NPP is critical to understand the carbon dynamics within the atmosphere-vegetation-soil continuum and the response of the terrestrial ecosystem to future climate change (Matsushita et al. 2004). Numerous models were developed to estimate global and regional NPP. Three types of models were generally used to estimate terrestrial NPP as described by Ruimy et al. (1994). They are: statistical models (Lieth 1973), parametric models (LAW et al. 1994; Prince et al. 1995), and process models (Bonan 1995; Liu et al. 1997). The first-type and second-type models are simple and easy to use, but they lack the strong theory and understanding of ecosystem function. Process models are on the basis of current knowledge of major ecological/biophysical processes and had many advantages such as the ability to handle interactions and feedbacks among different processes, and therefore, potentially produce more reliable results than other types of models. However, the process model is hampered by data availability and computing resources (Liu et al. 1997; Feng et al. 2007).

The role of global forests as a C sink is still under intensive investigation, as there are considerable uncertainties in the magnitude of the global C sink in different regions and the future responses of forests to climate change are quite uncertain (Liu et al. 2005; Schimel et al. 2001). One of the key factors creating uncertainties in estimating regional C sequestration and its spatial distribution is soil nitrogen (N) availability. Ecosystem carbon accumulation could be constrained by nutrients, particularly nitrogen (Hungate et al. 2003). A common failing of the above NPP models, however, is that the role of N in controlling the

conversion of carbohydrate to biomass is not described.

The Lantsang valley is originated from Tibetan Plateau with multiple climate zones and biological diversity. Further study of Lantsang valley would help to explore the relationship between NPP and the complicated environmental factors, especially the soil nitrogen availability. The objectives of the present study were (1) to develop an appropriate model of ecosystem N cycling suitable for inclusion in the Boreal Ecosystem Productivity Simulator (BEPS) by adding new N feedback controls on above-ground C assimilation; (2) to determine the effects of N on NPP of different climate zones by imposing a N cycle sub-model; (3) to explore spatial-temporal patterns of NPP in Lantsang valley. This study would provide a way for further exploring the impact of soil nutrient on ecosystem and well manage the eco-environment under global change.

Material and methodology

Study area

The Lantsang valley is located between 21°N and 34°N and between 94°E and 102°E (Fig.1). The total area is approximately 167 000 km^2 and its altitude rages from 500 m to 6 000 m. The upstream of Lantsang valley is on the Tibetan Plateau with permanently snow-capped high peaks, while, the most climate of the lower basin is tropical or sub-tropical. The Lantsang valley has a north-south gradient in temperature and precipitation caused by the latitude and terrain. The annual mean temperature is -3–22°C from north to south. The annual mean precipitation is 400–3 000 mm. The main soil types are alpine soil, leaching soil and acid soil for the upstream, midstream and downstream, respectively. The gradient of the dominant vegetation types are alpine meadow, coniferous forest, deciduous shrub, ever-green broadleaved forest and tropical/sub-tropical rain forest.

Field sampling

A quantitative survey of the soil types was implemented in October 2008 and June 2009, and totally 268 samples (0–10 cm, 10–20 cm and 20–30 cm) were collected covering all the soil types in this region. These soil samples were air dried, thoroughly mixed and passed through a 2-mm sieve to remove gravel and boulders. Measured soil factors involving total nitrogen (TN) and available nitrogen (AN) and the two parameters were measured with Elementar Vario MAX CN. To improve the precision of the results, three replicates were analyzed and averaged for each of the soil analyses. These two parameters were used to initial the N cycle sub-model.

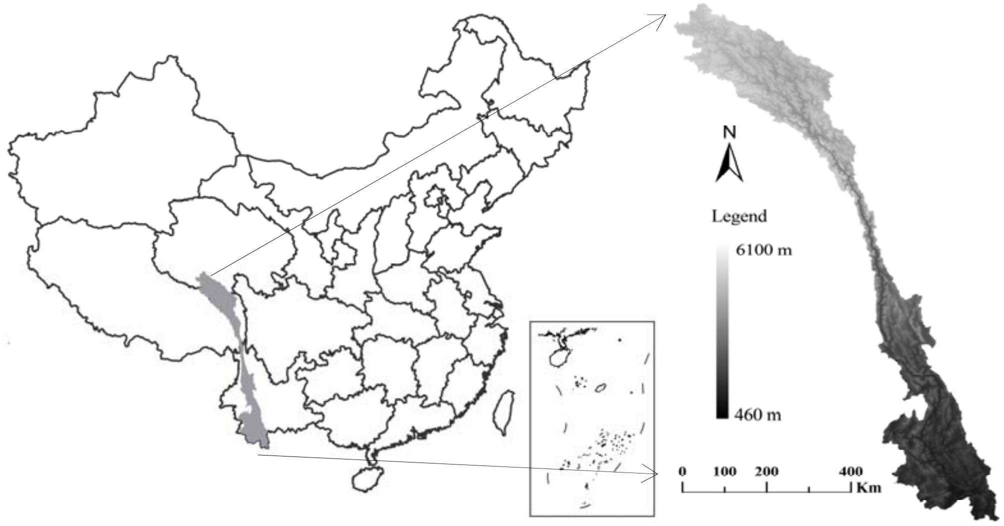

Fig.1 Location of the Lantsang valley

Data preparation

The main inputs to the model included land cover type, LAI (leaf area index), available soil-holding capacity (AWC), soil water content, DEM and daily meteorological data (including daily maximum and minimum air temperature, vapor pressure deficit, solar radiation and precipitation) in 2007.

Land cover and LAI were derived from MODIS satellite images. The meteorological data were from the National Meteorological Information Center, China Meteorological Administration. The land cover and LAI maps were at a 1 km resolution in a Lambert Conformal conic projection. Other data with different formats were reprocessed into the same resolution and projection as the satellite data. The soil parameters including AWC and soil water content were primarily determined by soil texture, and the soil parameters of the study area were clipped from China-wide map provided by Feng (2007). DEM data were derived from SRTM30 (Shuttle Radar Topography Mission: SRTM) and projected to the same coordinate system at 1 km resolution with other spatial data. The ANUSPLIN software, proven to be appropriate for spatial interpolation of climate, was used to inter-

polate the meteorological data except the radiation at 1 km resolution with terrain information. As solar radiation is a vital factor for NPP modeling and the solar radiation observations were limited, thus, an improved parameterized model for daily shortwave radiation on tilted surfaces described by Zhang et al. (2010) was adopted to estimate solar radiation. Biomass was from National Data Sharing Infrastructure of Earth System Science. The temporal intervals of the input data were annual for land cover, 10 days for LAI during the growing season, daily for meteorological data, and long-term for soil and biomass.

Model description

The improvement in this study was on the basis of the Boreal Ecosystem Productivity Simulator (BEPS), which combines remote sensing and ecosystem process approaches to quantify the terrestrial carbon cycle (Running et al. 1988). The BEPS model featured some advantages and improvements over other ecosystem models. First, the instantaneous photosynthesis model at leaf level was scaled up to the whole-canopy daily photosynthesis with a new temporal and spatial scaling scheme (Chen et al. 1999). Second, the BEPS model addressed the effect of canopy architecture on radiation interception by considering the dependence of radiation absorption on solar zenith angle due to the variation in the path length through the canopy (Liu et al. 1997). Third, it adjusted biophysical and biochemical parameters for the boreal ecosystems. In addition, the BEPS was well designed to address the problem of incorporating input data from different sources (e.g. satellite, GIS and ground weather station data) and the model runs at daily time step (Matsushita et al. 2004). In this study, the model was improved by importing a nitrogen sub-model. The details of the model are described as follows.

Canopy NPP was calculated by using original BEPS equations derived from the models of Farquhar et al. (1980). Since N is generally the most nutrient limiting to tree growth and often a limiting site factor to ecosystems, it is likely that any beneficial effects of elevated atmospheric CO_2 on NPP would be limited for the N limited ecosystems. The main purpose of N control is that soil mineral N determines both the ecosystem C flux and the ratios of C and N from the different mass fluxes associated with growth, senescence and decomposition. Because the N effect on NPP was not properly considered in the original BEPS model with a constant value of the leaf nitrogen content, some improvement was made in the proposed model on the basis of the N limitation equations proposed by Liu (2005). In the improved model, the actual maximum carboxylation V_m and the electron transport rate J_m varied from the notional unconstrained rate according to fluctuations in simulated leaf C : N (BL):

$$\begin{cases} V_m = (B_{V\max} / B_L) V_{\max} \\ J_m = (B_{J\max} / B_L) J_{\max} \end{cases} \tag{1}$$

Where, B_{Vmax} was the optimal foliar C : N (i.e., V_m=V_{max}). The equations indicated a simple feedback: when B_L was increased due to N limitation, V_m was decreased, and hence the maximum leaf photosynthesis rate was reduced.

The plant N pool was calculated on the basis of the theory of the plant-soil-atmosphere continuum. The portion of the nitrogen to the leaves was held a constant of the same vegetation type. The diagram of the overall N control and N budget is shown in Fig. 2. Plant N uptake from soil was assumed to be determined by plant N pool deficit and soil available N (net N mineralized, N inputs from fertilization and atmosphere minus any losses from the ecosystem). Carbon and nitrogen were transferred from vegetation to the litter (turnover) and from litter to soil organic matter (SOM).

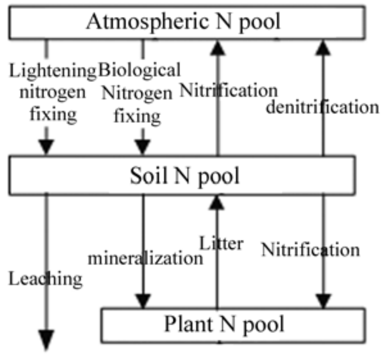

Fig.2 Diagram of N cycle of the ecosystem. The arrows represent N mass flow.

The instantaneous gross photosynthesis was calculated using Farquhar's model (Farquhar et al. 1980):

$$\begin{cases} A = \min\left(W_c, W_j\right) - R_d \\ W_c = V_m \dfrac{C_i - \Gamma}{C_i + K}; W_j = J_m \dfrac{C_i - \Gamma}{4.5Ci + 10.5\Gamma} \end{cases} \tag{2}$$

Where, A was net CO_2 assimilation rate, R_d was daytime leaf dark respiration, W_c and W_j are Rubwasco-limited and light-limited gross photosynthes rates, C_i was the intercellular CO_2 concentration, $\Gamma$was the CO_2 compensation point without dark respiration, and K was a function of enzyme kinetics.

At leaf level, daily average A was calculated through integration of photosynthetic rate. While at canopy level the total photosynthes was for sunlit and shaded leaves was calculated separately. NPP was GPP minus maintenance respiration (R_m) and growth respiration (R_g):

$$NPP = GPP - R_m - R_g \tag{3}$$

$$GPP = \int_{sunrise}^{sunset} (A_{sun} LAI_{sun} + A_{shade} LAI_{shade}) \tag{4}$$

Where, the subscript of "*sun*" and "*shade*" represented sunlit leaves and shaded leaves, respectively.

Results and discussion

Model comparison

The estimated NPP from the proposed model and BEPS were compared with field data of the study area (Table 1). There is not much difference between the improved model and the original BEPS for sub-tropical forest, as the soil nitrogen is sufficient in these areas, and the largest difference is conifer with 39 $g·m^{-2}·a^{-1}$ C due to the nitrogen limitation to the plant growth. For mountainous deciduous forest, the modeled NPP is somewhat lower than the measured NPP, while others had good agreement with the observed ones. The major factors contributing to differences in NPP are the differences in spatial scales between the modeled NPP with a spatial resolution of 1 km and the field observation representing single point. Overall, the modeled NPP is very close to the measured data, as many factors (tree age, climate, topography and modeling scale) could have influenced the accuracy of the simulated NPP.

Table 1. Comparison of ground data of NPP and simulated NPP ($g·m^{-2}·a^{-1}$ C)

Plot no.	location	Measured	Simulated*	Simulated**	Vegetation
22	yunnan	313–891.5	437	476	conifer
10	Sichuan	344.5–905.5	301	335	Mountainous deciduous forest
2	yunnan	552–864	632	658	Broadleaf forest
5	xizang	644–808	682	700	Evergreen broadleaf forest
31	yunnan	364–1660.5	933	952	Evergreen broadleaf forest
6	xizang	428–685.5	682	702	Sclerophyllous evergreen broad-leaved forest
38	yunnan	319.5–814	749	754	Sub-tropical mountainous forest
7	sichuan	360.5–712	599	599	Sub-tropical forest

Simulated* represented the averaged NPP simulated using the method proposed in the study. Simulated** represented the averaged NPP simulated using BEPS model. The measured NPP were cited from Luo (1997).

Spatial pattern of NPP in Lantsang valley

The average NPP and total NPP in 2007 over Lantsang valley were 416 $g·m^{-2}·a^{-1}$ C and 66.5 Tg C, respectively. The average GPP and total GPP were 791 $g·m^{-2}·a^{-1}$ C and 127 Tg C, respectively. The average autotrophic respiration and total autotrophic respiration were 641 $g·m^{-2}·a^{-1}$ C and 60.5 Tg C, respectively. The spatial distribution of NPP was associated with land cover and environmental factors. The NPP values had a north-south gradient resulted from temperature, DEM and precipitation. Statistical analysis for NPP of different land cover types simulated using the method proposed in this paper and BEPS (without considering the nitrogen effect) was shown in Table 2. The high NPP values occurred in the southern areas, especially the forests with warm climate and sufficient precipitation and radiation. The highest NPP (nearly 1 400 $g·m^{-2}·a^{-1}$ C) appeared in tropical/sub-tropical evergreen broadleaf forest of Yunnan. The lowest NPP values (lower than 50 $g·m^{-2}·a^{-1}$ C) were sparse vegetation in upstream of Qinghai province with insufficient temperature and precipitation resulting from higher altitude.

NPP by land cover per unit area: The simulated NPP values varied greatly with vegetation type and vegetation density (Table 2). Averaged for Lantsang valley in 2007, evergreen broadleaf forests (880.6 $g·m^{-2}·a^{-1}$ C) and mosaic lands (forest and grass, 670.8 $g·m^{-2}·a^{-1}$ C) absorbed the most carbon per unit area, followed by mixed forests (broadleaf and conifer, 529.8 $g·m^{-2}·a^{-1}$ C), croplands (446.4 $g·m^{-2}·a^{-1}$ C), conifer (289.6 $g·m^{-2}·a^{-1}$ C), shrub lands (199.5 $g·m^{-2}·a^{-1}$ C), and woody savannas (184.4 $g·m^{-2}·a^{-1}$ C). Mean NPP of barren or sparsely covered areas were much smaller (1.5 $g·m^{-2}·a^{-1}$ C).

Table 2 Area and average NPP of different land cover type

Land cover	Area (km^2)	Avg. NPP* ($g·m^{-2}·a^{-1}$ C)	Avg. NPP** ($g·m^{-2}·a^{-1}$ C)
Forest land	59940	685.3	685.8
Conifer	3855	289.6	290.5
Evergreen	3818	289.5	292.0
Deciduous	37	175.0	181.6
Broadleaf	33164	836.5	838.6
Evergreen	29597	880.6	882.7
Deciduous	3567	471.6	475.1
Mixed	22421	529.8	542.5
Shrub land	15265	199.5	214.4
Closed shrub land	2209	412.1	460.6
Open shrub land	13056	163.5	172.8
Woody savannas	65591	184.4	234.0
Savannas	3895	384.6	400.4
Grasslands	61696	171.7	223.5
Croplands	2582	446.4	533.5
Mosaic	14444	665.5	711.5
Forest/grass	14309	670.8	717.1
Crop/natural	135	102.3	118.19
Barren	2363	1.5	15.5
Urban and built-up	101	—	—
Snow and ice	141	—	—

Avg. NPP* represented the averaged NPP simulated using the method proposed in this paper; Avg. NPP** represented the averaged NPP simulated using BEPS model.

NPP by different regions per unit area: the climate characters

are quite different, as Lantsang valley covers 13 latitudes, and the terrain gradient is rather rough. The simulated NPP values vary with climate zones, because vegetation types and density are closely related to climate. Averaged for Lantsang valley, the dependence is as follows: upstream (14.6 $g \cdot m^{-2} \cdot a^{-1}$ C) < midstream (27.4 $g \cdot m^{-2} \cdot a^{-1}$ C) < downstream (62.5 $g \cdot m^{-2} \cdot a^{-1}$ C). The spatial variance of NPP also reflects the differences in ground conditions such as terrain and climate.

Temporal pattern of Lantsang valley NPP

The monthly average NPP distributions of different regions in Lantsang valley in 2007 were illustrated in Fig. 3. The results showed that the largest NPP occurred in July with 57.8 $g \cdot m^{-2} \cdot month^{-1}$ C, 74.8 $g \cdot m^{-2} \cdot month^{-1}$ C and 90.8 $g \cdot m^{-2} \cdot month^{-1}$ C for upstream, midstream and downstream, respectively. Because of the various climatic zones and vegetation distributions in Lantsang valley, the NPP temporal patterns varied greatly from north to south. The monthly variation of NPP for upstream is great. The monthly average NPP is lower than 10 $g \cdot m^{-2} \cdot month^{-1}$ C from November to April of next year, and the NPP was nearly zero during winter. The monthly average NPP of the downstream had little variation with a minimum value of 48.7 $g \cdot m^{-2} \cdot month^{-1}$ C in May. A possible explanation for the minimum NPP occurred in May was that the little radiation limited the photosynthesis caused by the coming wet-season in May.

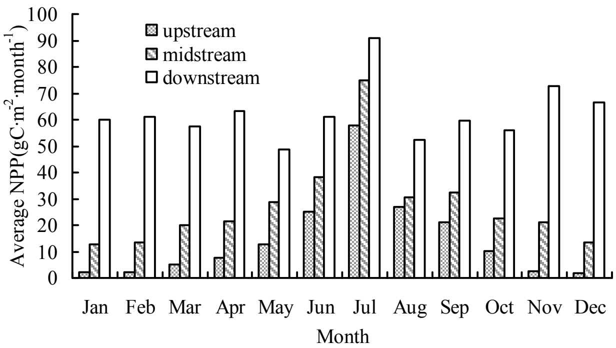

Fig. 3 The monthly average values of NPP in Lantsang valley

Conclusion

An improved process based model incorporating nitrogen effects on photosynthesis for simulating NPP was described, tested and used to simulate NPP distribution over Lantsang valley at 1 km resolution by using inputs derived from remote sensing and other metrological data in 2007. The total NPP and mean NPP of Lantsang valley in 2007 were 66.5 Tg C and 416 $g \cdot m^{-2} \cdot a^{-1}$, C respectively. The monthly average NPP of upstream had great variations while the downstream differs slightly. The insufficient of soil available nitrogen might be another limitation of the carbon fixing besides temperature and precipitation for the upstream of Lantsang valley. The model also shows nitrogen has no evident limitation to NPP accumulation of downstream.

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